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AMINOSTRATIGRAPHY AND OXYGEN ISOTOPE STRATIGRAPHY OF MARINE-TERRACE DEPOSITS, PALOS VERDES HILLS AND SAN PEDRO AREAS, LOS ANGELES COUNTY, CALIFORNIA

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ABSTRACT: Amino-acid and oxygen isotope data for fossils from terraces of the Palos Verdes Hills and San Pedro areas in Los Angeles County, California, shed new light on the ages of terraces, sea-level history, marine paleotemperatures, and late Quaternary tectonics in this region. Low terraces on the Palos Verdes peninsula correlate with the ~80-ka and ~125-ka sea-level highstands that are also recorded as terraces on other coasts. In San Pedro, the Palos Verdes sand (the deposit on what is mapped as the first terrace by Woodring and others, 1946) was previously thought to be a single deposit; amino-acid, oxygen isotope, U-series, and faunal data indicate that deposits of two ages, representing the 80-ka and 125-ka highstands occur within this unit. Oxygen isotope data show that on open, exposed parts of the Palos Verdes peninsula, ocean waters during the 125-ka highstand were cooler than present (by about 2.3–2.6°C) similar to what has been reported for other exposed coastal areas in California. In contrast, in the protected embayment environment around San Pedro, water temperatures during the 125-ka highstand were as warm or warmer than present. During the 80-ka highstand, water temperatures were significantly cooler than present even in the relatively protected embayment environment of the San Pedro area.

Late Quaternary tectonic-uplift rates can be calculated from terrace ages and elevations. Correlation of the lowest terraces around the Point Fermin area shows that the Cabrillo fault has a late Quaternary vertical-movement rate of 0.20 m/ka, based on the difference in uplift rates on the upthrown and downthrown sides of the fault. Elsewhere in the Palos Verdes Hills–San Pedro area, late Quaternary uplift rates vary from 0.32 m/ka to possibly as high as 0.72 m/ka. These rates, which reflect vertical movement on the Palos Verdes fault, are in broad agreement with estimated Holocene vertical rates of movement determined for offshore portions of the fault.

INTRODUCTION

The marine-terrace sequence in the Palos Verdes Hills–San Pedro area of southern California (Fig. 1), where 13 terraces rise to an elevation of almost 400 m, has long attracted the attention of researchers. Marine terraces in California, like those on many other tectonically active coastlines, record interglacial sea-level highstands superimposed on long-term tectonic uplift. Because of the number of terraces and their elevations, the Palos Verdes Hills area has been of interest for providing a detailed record of these combined processes of sea-level fluctuations and tectonics.

Critical to developing sea-level and tectonic history of a flight of marine terraces is reliable dating of the terrace deposits. Several attempts have been made to date the marine terraces on the Palos Verdes Hills. Uranium-series methods were applied to marine-terrace mollusks by Fanale and Schaeffer (1965), Szabo and Rosholt (1969), Szabo and Vedder (1971), and Kaufman and others (1971). However, it is now known that mollusks take up uranium secondarily and do not always form closed systems with respect to ^{238}U and its long-lived daughter products (Kaufman and others, 1971). The open-system uranium-trend dating method was applied to some of the Palos Verdes Hills terraces (Muhs and others, 1989), but this method is still experimental. One of the earliest feasibility studies for amino-acid geochronology studies was conducted on shells collected from terraces of the Palos Verdes Hills (Mitterer and Hare, 1967). Age estimates for marine-terrace mollusks based on amino-acid racemization were also reported by Wehmiller and others (1977), Muhs (1984), Bryant (1987), and Wehmiller (1990), but these studies were limited both in the number of localities sampled and in the number of shells analyzed at each locality. Thus, much remains to be learned about the ages of terraces in the Palos Verdes Hills–San Pedro area.

This study presents amino-acid and oxygen isotope data for marine-terrace mollusks that shed new light on terrace ages. With these age estimates, it is possible to correlate terrace-forming intervals with sea-level events recorded on other coasts. Late Quaternary sea-level highstands have been recorded on other coasts at ~60 ka, ~80 ka, ~105 ka, ~125 ka, and 190 to 220 ka (Mesolella and others, 1969; Veeh and Chappell, 1970; James and others, 1971; Bloom and others, 1974; Dodge and others, 1983; Harmon and others, 1983; Edwards and others, 1987; Bard and others, 1990; Ku and others, 1990; Muhs and others, 1992). Oxygen isotope data also provide information on ocean paleotemperatures. Ocean paleotemperatures estimated from oxygen isotope data for this area are compared with similar data for other parts of the Pacific Ocean bordering the United States (Valentine and Meade 1961; Muhs and Kyser, 1987; Muhs and others, 1990). In addition to their importance in developing a local sea-level chronology, terrace ages can, when combined with marine-terrace shoreline-angle (inner-edge) elevations and corrected for sea-level fluctuations, yield long-term average rates of tectonic uplift. From these data, we can infer at least minimum late Pleistocene vertical-slip rates for the faults that occur around or on the Palos Verdes Hills area, such as the Palos Verdes Hills and Cabrillo faults. Both of these faults extend offshore to the southeast of the Palos Verdes Hills. Late Pleistocene–Holocene slip rates have been calculated for the offshore portions of these faults

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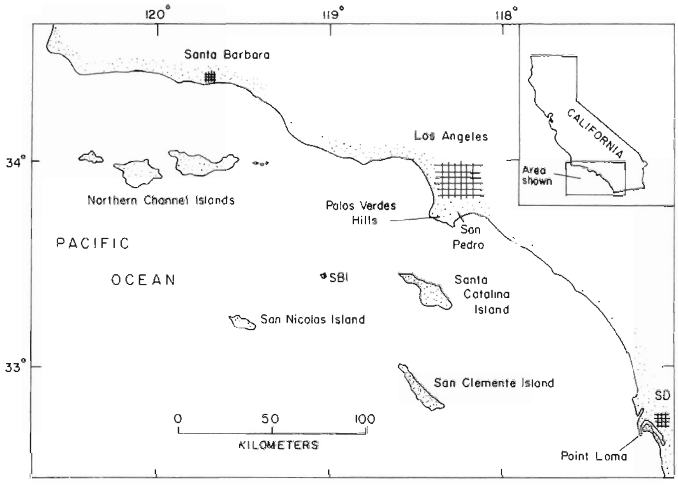

FIG. 1.—Index map of coastal southern California showing location of the Palos Verdes Hills, San Pedro, and other localities referred to in the text. SBI, Santa Barbara Island; SD, San Diego.

km from the Santa Monica shelf south to near Lasuen Knoll, which is west of the city of San Clemente (Fischer and others, 1987). The only onshore expression of the fault is in the Palos Verdes Hills area. The Palos Verdes Hills fault also has a vertical component of movement, which is reverse, south side up (Yerkes and others, 1965; Nardin and Henyey, 1978; Fischer and others, 1987). The 13 elevated marine terraces on the Palos Verdes Hills are one of the main expressions of Quaternary activity of the Palos Verdes Hills fault, but Fischer and others (1987) documented that late Pleistocene and Holocene offshore sediments are also displaced by the fault. They reported vertical offsets of Holocene shelf sediments, *en echelon* topographic anomalies, and seafloor scarps, and they estimated average Holocene vertical-slip rates of about 0.1 to 0.4 m/ka for the offshore portion of the Palos Verdes Hills fault. Parts of the Palos Verdes Hills crustal block are also displaced by the smaller Cabrillo fault (Fig. 2). Fischer and others (1987) estimated an average Holocene vertical-slip rate of 0.4 to 0.7 m/ka for the offshore portion of the Cabrillo fault.

by Fischer and others (1987). Age estimates for the marine terraces allow a comparison of slip rates between onshore and offshore portions of the faults.

STRUCTURAL GEOLOGY

The Palos Verdes peninsula–San Pedro area is bounded on its northeast, landward side by the northwest-trending Palos Verdes Hills fault (Fig. 2). This fault, which Nardin and Henyey (1978) interpreted to have experienced dextral strike slip during the Quaternary, extends more than 100

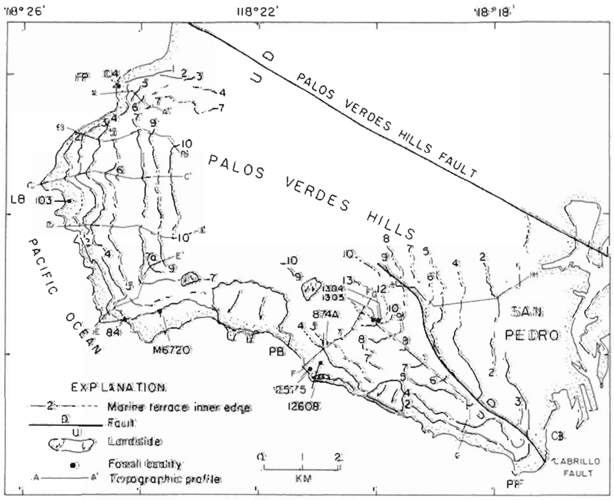

FIG. 2.—Map of the Palos Verdes Hills–San Pedro area showing marine-terrace inner edges, major faults, fossil localities outside of San Pedro, and locations of topographic profiles. Terrace inner edges are taken from Woodring and others (1946), and terrace numbering system is unchanged from those authors. Location of Palos Verdes Hills and Cabrillo faults from Junger and Wagner (1977) and Woodring and others (1946). FP, Flatrock Point; LB, Lunada Bay; PB, Portuguese Bend; PF, Point Fermin; CB, Cabrillo Beach.

MARINE TERRACES

Marine terraces on the Palos Verdes Hills are generally well expressed topographically, although urbanization has significantly modified the natural landscape. Woodring and others (1946) mapped in detail the terraces in both the Palos Verdes Hills (Fig. 2) and San Pedro areas (Fig. 3). Our field observations and interpretation of 1954 (1:20,000) and 1972 (1:30,000) aerial photographs confirm the general landform mapping of these previous workers. Thus, the terraces mapped in Figures 2 and 3 are derived from Woodring and others (1946) and the terrace numbers on those maps are unchanged from their nomenclature. On the basis of new platform-elevation measurements, Bryant (1987) suggested that many more terraces may be present than originally mapped by Woodring and others (1946). However, individual terrace boundaries can be clearly defined only by the location of the inner edge, or shoreline angle, which is the junction of the marine platform and the sea cliff. Bryant's (1987) new elevation measurements appear to be of the marine platforms rather than the shoreline angles, so his hypothesis of additional terraces must await further field study. For the purposes of our study, we have assumed that the map of Woodring and others (1946) is basically correct in terms of landform mapping but not necessarily in terms of lateral correlation of terrace segments.

The best reference point on a marine terrace for paleosea-level or uplift-rate studies is the shoreline angle. In the San Diego area, modern shoreline angles are usually formed within 1 m of present mean sea level (Kern, 1977). Unfortunately, shoreline angles of uplifted marine terraces are rarely exposed in southern California because the sides of canyons that dissect the terraces are usually covered with colluvium. In addition, urbanization has removed or obscured many exposures. The topographically defined inner edges of even well-preserved terraces have elevations that are usually greater than the shoreline-angle elevations because wedges of colluvium or alluvium have accumulated at the bases of the former sea cliffs. The post-emergence

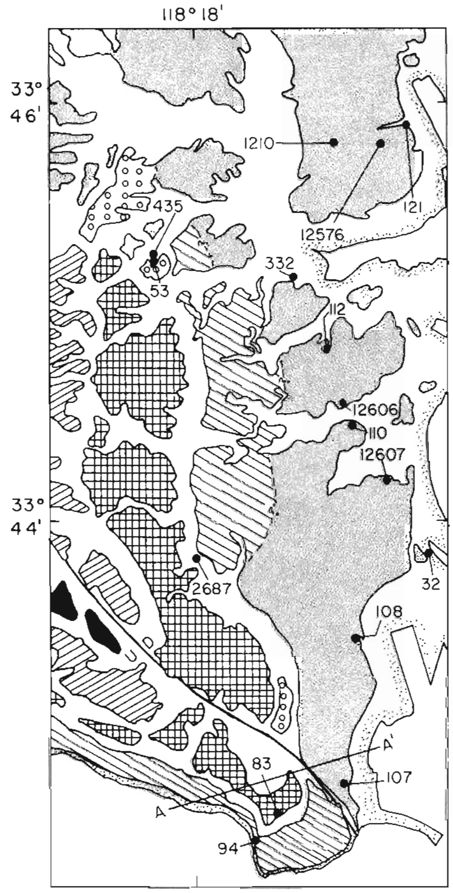

FIG. 3.—Map of marine terraces (modified from Woodring and others, 1946) and fossil localities in the San Pedro area. Inner edge of the first terrace (Palos Verdes sand) is not well expressed at most places and was not mapped in many places by Woodring and others (1946); contacts shown here are approximate. Terrace numbering system is unchanged from Woodring and others (1946). Cross section A–A′ is shown in Figure 10.

terrace-sedimentation history in the Palos Verdes Hills area is highly complex and precludes the use of soils as a reliable mapping and correlation tool.

In order to estimate shoreline-angle elevations on these sediment-covered terraces, we enlarged the shore-normal topographic profiles (locations shown on Fig. 2) constructed by Woodring and others (1946) and projected the outer-platform gradient inland and the maximum slope angle on the sea cliff downward. The intersection of these projections is the approximate position of the shoreline angle, and the elevations are probably accurate to within ±4 m, based on graphical errors alone. Other errors are present because the marine and terrestrial covers of the terraces vary both in thickness and shore-normal extent, but we cannot estimate the magnitude of these errors because there are so few good exposures.

Using these approximate shoreline-angle elevations and estimates of the elevations of the outer-platform edges, we constructed shore-parallel profiles of the terraces in order to examine terrace continuity and to evaluate terrace correlations as mapped by Woodring and others (1946) (Fig. 4). However, correlation of some of the lower terraces, as shown on Figure 4, is based on aminostratigraphic data, as discussed later. Results indicate that even within the rather large uncertainty of the shoreline-angle elevation measurements, the lower terraces can be correlated laterally and are essentially horizontal from topographic profile B north of Lunada Bay southeast to topographic profile F, on the southeast side of the Portuguese Bend landslide. However, elevations of terraces along topographic profiles A, G, and H do not match well with elevations of terraces along profiles B through F (Fig. 4). Profile A, near Flatrock Point, is in an area that has a northwest-trending fault (normal, south side up; described by Riccio and Mills, 1977) that displaces terrace deposits and overlying non-marine deposits. This fault was not previously identified by Woodring and others (1946), and it is possible that the terraces on profile A do not correlate with those on profile B because of displacements by this or other faults. Profiles G and H are on the upthrown and downthrown sides, respectively, of the Cabrillo fault (Fig. 2). It is possible that the terraces in this area have been displaced along the Cabrillo fault, and terrace correlation across the fault based on shoreline-angle elevation has not been attempted. One of our goals was to seek terrace fossils on both sides of the Cabrillo fault that would enable us to make lateral correlations that are not based on shoreline-angle elevation.

URANIUM-SERIES DATING

Corals are the most suitable materials for uranium-series dating, but unfortunately few corals occur in most marine-terrace deposits of the Pacific Coast of North America. Nevertheless, some solitary corals and colonial hydrocorals have been recovered, and in recent years a number of new U-series ages have been generated (Muhs and Szabo, 1982; Rockwell and others, 1989; Muhs and others, 1990, 1992; Muhs, 1992). These recent studies are important to our study

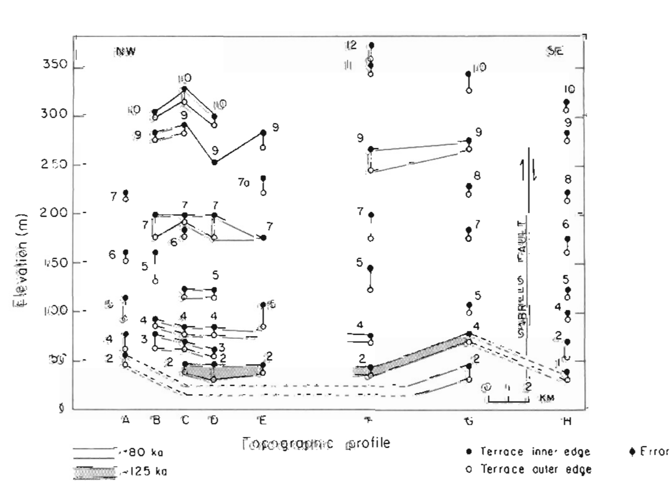

FIG. 4.—Shore-parallel profiles of marine-terrace inner and outer edges in the Palos Verdes Hills and San Pedro. Probable correlations, based on either elevation or amino-acid and stable-isotope data, are shown by solid lines; tentative correlations are shown by dashed lines.

because they provide localities from which amino-acid ratios can be calibrated. Three of these localities, San Clemente Island, San Nicolas Island, and Point Loma near San Diego (Fig. 1), are close to the Palos Verdes Hills and San Pedro. U-series analysis of coral from the lowest two terraces at Point Loma and San Nicolas Island indicate that the terraces are ~80 ka and ~125 ka (Ku and Kern, 1974; Muhs and others, 1992; Muhs, 1992). Muhs and Szabo (1982) reported an age of 127±7 ka for a hydrocoral from the second terrace on San Clemente Island.

It is now known that U-series ages of fossil mollusks are not reliable because these organisms do not take up uranium from seawater during growth and often act as open systems with respect to uranium and its daughter products after death (Kaufman and others, 1971). However, in cases where there are concordant $^{230}Th/^{234}U$ and $^{231}Pa/^{235}U$ ages, these are reliable *minimum* age estimates for fossil mollusks. Szabo and Rosholt (1969) report U-series analyses of fossil mollusks collected from the first terrace in San Pedro near locality 112 (Fig. 3) of Woodring and others (1946). Four of their samples showed concordant $^{230}Th/^{234}U$ and $^{231}Pa/^{235}U$ ages within limits of analytical error, indicating that these four samples have been closed systems with respect to ^{238}U, ^{235}U, and their daughter products since initial uranium uptake. Thus, we can regard the calculated ages as reasonable minimum ages for the shells. The calculated $^{230}Th/^{234}U$ ages range from 92±8 ka to 110±6 ka, and the oldest age is the closest minimum age of the deposit. Thus, deposits of the first terrace in this part of San Pedro are no younger than about 104 ka, based on the analytical uncertainty. The first terrace deposits in northern San Pedro could therefore have been deposited during the highstands recorded on other coasts at ~105 ka or ~125 ka but could not have been deposited during the ~60-ka or ~80-ka highstands.

AMINO-ACID GEOCHRONOLOGY

Principles of Amino-Acid Geochronology

Aminostratigraphy is based on the observation that the protein of living organisms contains only amino acids of the L (lero, or left handed) configuration. Upon death of an organism, amino acids of the L configuration convert to amino acids of the D (dextro, or right handed) configuration, a process referred to as racemization. A similar process, called epimerization, is the conversion of L-isoleucine (Ile) to D-alloisoleucine (aIle). Racemization and epimerization are reversible reactions that result in increased D/L or aIle/Ile ratios through time until an equilibrium ratio of 1.00 to 1.30 (depending on the amino acid) is reached. Thus, in a simplified view, a higher aIle/Ile or D/L ratio in a fossil indicates a relatively greater age. Amino-acid ratios in fossils are also highly dependent on environmental temperature history, genus, and a variety of diagenetic processes (see Miller and Hare, 1980; Wehmiller, 1982; Miller and Brigham-Grette, 1989; and Muhs, 1991, for reviews). The simplest application of amino-acid ratios in geochronological studies is relative age determination and lateral correlation, or "aminostratigraphy" (Miller and Hare, 1980). The main assumption in this approach is that localities studied have had roughly similar temperature histories. Stratigraphic units containing mollusks with amino-acid ratios that cluster around a certain value can be identified as "aminozones" (Nelson, 1982).

In this study, two different methods for amino-acid analyses were employed. Analyses conducted at the University of Colorado used liquid chromatography. The method in use at that laboratory at present is referred to as "method A" and is described in detail by Miller (1985). Liquid-chromatography methods only resolve D-alloisoleucine and L-isoleucine as separate isomers; D and L configurations of other amino acids are not resolved. Analyses conducted at the University of Delaware used gas chromatography. This method does not resolve D-alloisoleucine and L-isoleucine well but does resolve the D and L isomers of several other amino acids. Some of the data obtained by gas chromatography were previously reported by Wehmiller and others (1977), but new data are reported here. Detailed analytical methods for gas chromatography are given by Wehmiller and others (1977).

Amino-Acid Ratios in Mollusks from Dated Terraces on San Nicolas Island

Because of the paucity of corals suitable for uranium-series dating in terrace deposits of the Palos Verdes Hills, we used amino-acid ratios in dated terraces from nearby study areas. As discussed earlier, the two lowest terraces on San Nicolas Island have corals with U-series ages of ~80 ka and ~125 ka. We collected specimens of the gastropod *Tegula* and the bivalve *Epilucina*, two of the most common genera in the Palos Verdes Hills, from the dated San Nicolas Island terraces (Fig. 5) to determine whether either of them could discriminate between 80-and 125-ka deposits. Some of these data were previously reported by Muhs (1985), but most are new.

Results indicate that *Tegula* is a relatively good discriminator of 80-ka and 125-ka deposits (Table 1). Five *Tegula*

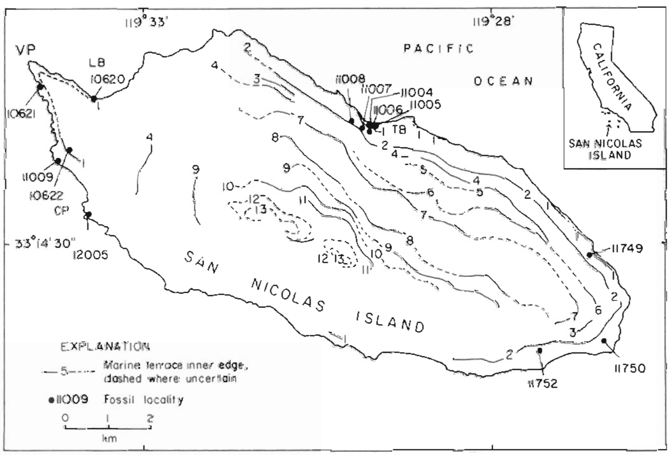

FIG. 5.—Map of inner edges of marine terraces and fossil localities on San Nicolas Island. All inner-edge data are from Vedder and Norris (1963) with the exception of those the first terrace, which was mapped by D. R. Muhs and G. L. Kennedy. VP, Vizcaino Point; CP, Cormorant Point; LB, Laser Bay; TB, Tranquility Beach.

TABLE 1.—RATIOS OF D-ALLOISOLEUCINE TO L-ISOLEUCINE (AILE/ILE) IN *TEGULA* AND *EPILUCINA* FROM U-SERIES-DATED 80-KA AND 125-KA TERRACES ON SAN NICOLAS ISLAND (SNI) AND SAN CLEMENTE ISLAND (SCI) USING LIQUID CHROMATOGRAPHY.

Location[1]	LACMNH Loc.[2]	Terrace	U-series Age (ka)	Genus	AAL[3]	aIle/Ile	Mean±s.d.
SNI, LB	10620	1	80	*Tegula*	5035A	0.36	
					B	0.28	
					C	0.20	
					D	0.29	0.28±0.05
					E	0.29	(n = 5)
SNI, TB	11006	2	125	*Tegula*	3653A	0.50	
					B	0.47	
					C	0.45	
					D	0.35	
					E	0.42	
					5276A	0.46	
					B	0.45	
					C	0.35	
					D	0.37	
					E	0.48	
SNI, VP	10622	2	125	*Tegula*	5038B	0.48	
					C	0.54	
					D	0.56	0.46±0.06
					E	0.52	(n = 14)
SNI, TB	11004	1	80	*Epil.*[4]	3651A	0.33	
					B	0.35	
					C	0.29	
					D	0.34	
					E	0.29	
SNI, CP	12005	1	80	*Epil.*[4]	5039A	0.34	
					B	0.30	
					C	0.43	
					D	0.30	
					E	0.34	
SNI, LB	10620	1	80	*Epil.*[4]	5034A	0.36	
					B	0.39	
					C	0.34	
					D	0.39	
					E	0.34	
SNI, VP	10621	1	80	*Epil.*[4]	5036A	0.40	
					B	0.41	
					C	0.48	
					D	0.40	0.36±0.05
					E	0.40	(n = 20)
SNI, TB	11006	2	125	*Epil.*[4]	3652A	0.34	
					B	0.38	
					C	0.30	
					D	0.34	
					E	0.47	
					5290A	0.45	
					B	0.40	
					C	0.34	
					D	0.37	
					E	0.34	
SNI, VP	10622	2	125	*Epil.*[4]	5037A	0.52	
					B	0.40	
					C	0.47	
					D	0.47	0.41±0.07
					E	0.50	(n = 15)
SCI, EP	10725	2	125	*Tegula*	3650A	0.59	
					B	0.58	
					C	0.60	
					D	0.56	0.59±0.02
					E	0.60	(n = 5)

[1]SNI, San Nicolas Island; LB, Laser Bay; TB, Tranquility Beach; VP, Vizcaino Point; CP, Cormorant Point; SCI, San Clemente Island; EP, Eel Point.
[2]LACMNH, Los Angeles County Museum of Natural History fossil locality.
[3]AAL, Amino Acid Laboratory (University of Colorado) number.
[4]*Epilucina californica*.

individuals from the 80-ka terrace gave a mean aIle/Ile of 0.28±0.05, whereas 14 *Tegula* individuals from the 125-ka terrace gave a mean aIle/Ile of 0.46±0.06. If we omit the four individuals from the relatively shallow terrace deposit at locality 10622, where surface-heating effects may have taken place, the mean for the 10 remaining individuals is 0.43±0.05, still significantly higher than the mean for the shells from the 80-ka terrace. Thus, we are confident that *Tegula* can discriminate between 80-ka and 125-ka deposits.

The results for *Epilucina* indicate that this genus is not effective for discriminating between 80-ka and 125-ka deposits (Table 1). The mean aIle/Ile for 20 individuals from the 80-ka terrace is 0.36±0.05, and the mean for 15 individuals from the 125-ka terrace is 0.41±0.07, which is not significantly different. This difference is reduced even further if we eliminate the five individuals from locality 10622 (again, where the terrace deposit is shallow and surface-heating effects may have taken place); the resultant mean of 10 individuals from the 125-ka terrace is 0.37±0.05, which is almost identical to the ratio for the 80-ka-terrace shells. Muhs (1985) showed that *Epilucina* was effective in discriminating only two broad relative ages among terraces 1, 2, 4, 5, and 10 on San Nicolas Island. We conclude that *Epilucina* may be capable of distinguishing late Quaternary from middle or early Quaternary terraces, but this genus cannot discriminate between 80-ka and 125-ka terraces.

For most of our investigations in the Palos Verdes Hills and San Pedro areas, *Tegula* amino-acid data were used, based on the demonstrated suitability of this genus on San Nicolas Island. *Tegula* occurs primarily in exposed, high-energy, rocky-shore environments, but is largely absent in protected, sandy, quiet-water environments such as embayments. Quiet environments are more common than high-energy environments in San Pedro. For these localities, we rely on the bivalve *Protothaca staminea*, which is common in the terrace deposits.

Aminostratigraphy of Low-Elevation Terrace Deposits in San Pedro and the Palos Verdes Hills

In order to correlate deposits in the Palos Verdes Hills and San Pedro areas with the dated terraces on San Nicolas Island, we sought low terrace sequences that, based on independent evidence, could correspond to the 80-ka and 125-ka highseastands. Kennedy and others (1982) showed that in many parts of the Pacific coast of the United States, 125-ka-terrace deposits commonly contain extraliminal southern species, whereas 80-ka-terrace deposits contain significant numbers of extraliminal northern species. In the Point Fermin area of San Pedro, on the upthrown side of the Cabrillo fault (Figs. 2 and 3), the two lowest terraces are mapped as terrace "2" and terrace "4" by Woodring and others (1946). The fauna of the "fourth" terrace (locality 83, Fig. 3) was described in detail by Valentine (1962) and contains three extralimital southern species, *Bernardina bakeri*, *Crassinella pacifica*, and *Acanthina lugubris*. In contrast, the fauna on the "second" terrace (locality 94, Fig. 3) was studied by Chase and Chace (1919) and contains a number of extraliminal northern species. Thus, this terrace pair appeared to be a possible 80-ka to 125-ka pair, and accordingly *Tegula* was analyzed from this sequence. The results support our hypothesis when compared with dated deposits on San Nicolas and San Clemente Islands (Table

2 and Fig. 6). In Figure 6, the mean aIle/Ile ratios in *Tegula* are plotted as a function of current mean annual temperature. Mean aIle/Ile ratios should increase with higher integrated thermal histories, which we believe can be proxied crudely by present mean annual air temperatures. The mean aIle/Ile ratio in *Tegula* from the ''fourth'' terrace at Point Fermin is significantly higher than that for *Tegula* from the ''second'' terrace; these two means are slighter higher, respectively, than those from the 125-ka and 80-ka terraces on cooler San Nicolas Island. Because San Clemente Island has about the same mean annual air temperature as San Pedro, we would expect similar mean aIle/Ile ratios in the ''fourth'' terrace at Point Fermin and the 125-ka terrace on San Clemente Island. Our results support this hypothesis, as the the two ratios (0.58±0.05 and 0.59±0.02) are not significantly different (Tables 1 and 2; Fig. 6). We therefore correlate the ''fourth'' and ''second'' terraces on Point Fermin with the ~125-ka and ~80-ka highstands of sea level, respectively.

Using this terrace pair at Point Fermin as a starting point, terraces around the Palos Verdes peninsula and in the San Pedro area can be correlated using amino-acid ratios. What has been mapped as the ''second'' terrace at Flatrock Point (locality 104) has ratios that suggest correlation with the ''second'' terrace at Point Fermin, but the ''second'' terrace localities at Lunada Bay (locality 103) and southeast of Portuguese Bend (locality 12575) suggest correlation with the ''fourth'' terrace at Point Fermin (Table 2 and Fig. 7). On the downthrown side of the Cabrillo fault, a low terrace has been mapped as the ''first'' terrace by Woodring and others (1946). We collected *Tegula* from locality 108 on this terrace (Fig. 3), a locality that is referred to in the older literature as ''Crawfish George's.'' This locality is significant in that it contains a distinct cool-water fauna, with at least eight extralimital northern species and only three extralimital southern species (Valentine and Meade, 1961). The mean aIle/Ile ratio for *Tegula* from this locality is 0.37±0.05, which is identical to the mean ratio for *Tegula* from the ''second'' terrace at Point Fermin. The cool-water aspect to the faunas from both localities further reinforces this correlation (Fig. 7). Thus, amino-acid data for *Tegula* indicate that segments of the ''second'' terrace as mapped by Woodring and others (1946) are not the same age everywhere; some segments are correlative with what has been mapped as the ''fourth'' terrace, and other segments are correlative with what has been mapped as the ''first'' terrace.

Comparison of *Protothaca* data from two localities where both *Protothaca* and *Tegula* are present indicates that *Protothaca* can also be used to differentiate and correlate terraces in this area. As discussed earlier, we correlate the ''second'' terrace at locality 12575 with the ~125-ka highstand on the basis of the *Tegula* data. *Protothaca* shells from this locality have a mean aIle/Ile ratio of 0.35±0.02. At Crawfish George's, *Tegula* data suggest correlation of this deposit with the 80-ka highstand, and *Protothaca* shells have a mean aIle/Ile ratio of 0.28±0.04. Using these two localities for calibration, the age of the lowest mapped terrace within San Pedro can be evaluated. Based on *Protothaca* data, the deposit exposed at 8th and Center Streets

TABLE 2.—RATIOS OF D-ALLOISOLEUCINE TO L-ISOLEUCINE (AILE/ILE) IN *PROTOTHACA* AND *TEGULA* FROM MARINE-TERRACE DEPOSITS IN SAN PEDRO AND THE PALOS VERDES HILLS (PVH), CALIFORNIA, USING LIQUID CHROMATOGRAPHY.

Location[1]	Fossil Loc.[2]	Terrace[3]	Species[4]	AAL[5]	aIle/Ile	Mean±s.d.
San Pedro	12607	1	*P.s.*	6459A	0.22	0.28±0.07
				B	0.26	(n = 5)
				C	0.42	
				D	0.25	
				E	0.25	
San Pedro	WBK 108	1	*P.s.*	5361A	0.27	0.28±0.04
				B	0.29	(n = 5)
				C	0.29	
				D	0.21	
				E	0.32	
San Pedro	12606	1	*P.s.*	5362A	0.40	0.36±0.03
				B	0.35	(n = 4)
				C	0.32	
				D	nd	
				E	0.35	
San Pedro	12576	1	*P.s.*	6456A	0.38	0.34±0.04
				B	0.29	(n = 6)
				C	0.34	
				D	0.32	
				E	0.30	
				F	0.39	
PVH	12575	2	*P.s.*	6457A	0.35	0.35±0.02
				B	0.34	(n = 4)
				C	0.38	
				D	0.32	
PVH	12608	4	*P.s.*	6460A	0.44	0.40±0.04
				B	0.36	(n = 2)
San Pedro	WBK 108	1	*T.f.*	5360A	0.36	0.37±0.05
				B	0.46	(n = 5)
				C	0.32	
				D	0.34	
				E	0.37	
San Pedro	WBK 94	2	*T.f.*	6466A	0.40	0.37±0.08
				B	0.28	(n = 5)
				C	0.52	
				D	0.32	
				E	0.32	
PVH	WBK 104	2	*T.*sp.	6465A	0.44	0.39±0.03
				B	0.39	(n = 5)
				C	0.38	
				D	0.37	
				E	0.35	
PVH	WBK 103	2	*T.*sp.	5359A	0.56	0.47±0.06
				B	0.48	(n = 5)
				C	0.48	
				D	0.38	
				E	0.46	
PVH	12575	2	*T.f.*	6458A	0.56	0.53±0.05
				B	0.48	(n = 5)
				C	0.48	
				D	0.52	
				E	0.60	
San Pedro	WBK 83	4	*T.*sp.	5358A	0.62	0.58±0.05
				B	0.51	(n = 5)
				C	0.62	
				D	0.62	
				E	0.54	
PVH	12608	4	*T.*sp.	6461A	0.66	0.65±0.05
				B	0.59	(n = 5)
				C	0.73	
				D	0.67	
				E	0.62	

[1]PVH, Palos Verdes Hills.
[2]All fossil localities are Los Angeles County Museum of Natural History localities except those preceded by WBK, which are from Woodring and others (1946). It should be noted that although fossils used here were collected from or near localities of Woodring and others (1946), they were collected by the authors, not Woodring and others (1946).
[3]Terrace numbers refer to nomenclature of Woodring and others (1946).
[4]Species: *P.s.*, *Protothaca staminea; T.f.*, *Tegula funebralis; T.*sp., *Tegula* sp.
[5]AAL, Amino Acid Laboratory (University of Colorado) number.

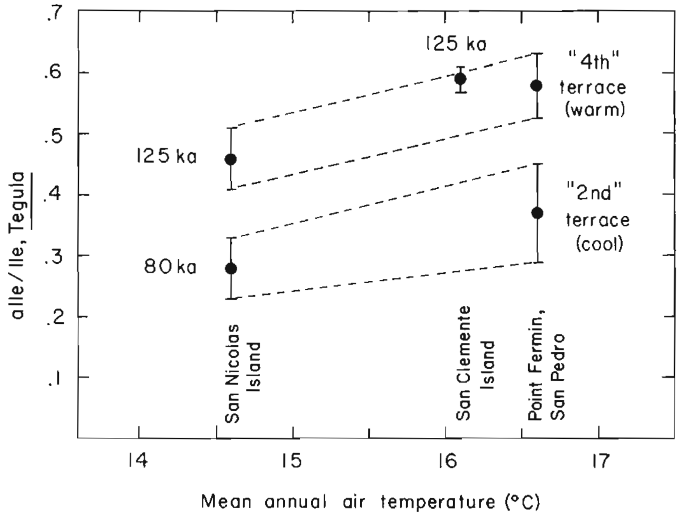

FIG. 6.—Mean aIle/Ile ratios in *Tegula* plotted as a function of mean annual air temperature, showing aminostratigraphic correlation of marine terraces in the Point Fermin area with U-series-dated marine terraces on San Nicolas Island and San Clemente Island. "Warm" and "cool" refer to thermal aspects of the terrace faunas.

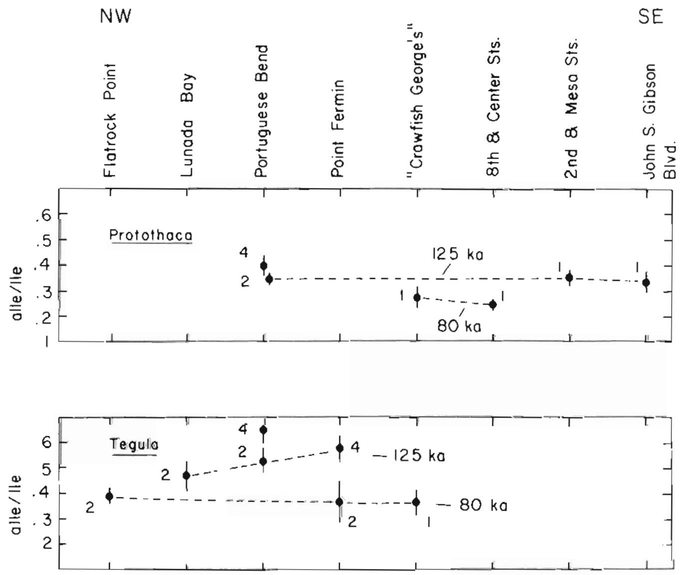

FIG. 7.—Aminostratigraphic correlation of marine terraces in the Palos Verdes Hills–San Pedro area in a northwest-southeast direction, based on aIle/Ile ratios in *Protothaca* and *Tegula*. Terrace numbers given are those of Woodring and others (1946).

(locality 12607) correlates with the ~80-ka highstand, and the deposits at 2nd and Mesa Streets (locality 12606) and John S. Gibson Boulevard (locality 12576) correlate with the ~125-ka highstand. Although Woodring and others (1946) mapped a large area within San Pedro as belonging to the "first" terrace (Fig. 3), our data indicate that two ages of deposits are present within this mapping unit. D/L ratios of other amino acids (leucine, glutamic acid, valine, alanine, proline, and phenylalanine) (Table 3) from *Tivela, Macoma*, and *Protothaca* support this conclusion.

Locality 121 is near locality 12576 in northern San Pedro (Fig. 3), and shells from the former show higher D/L ratios for most amino acids than those from shells collected from locality 110, near 3rd and Mesa Streets in central San Pedro (Fig. 8). The magnitude of difference as it pertains to age is best shown by comparison with *Protothaca* D/L data reported by Wehmiller and others (1977) for the two low terraces found on Point Loma near San Diego. The older of these two terraces, the Nestor terrace, has a coral U-series age of about 125 ka, and the lower Bird Rock terrace has a coral U-series age of ~80 ka, as discussed earlier. Comparison of D/L ratios in *Protothaca* from the Point Loma terraces with those from San Pedro (Fig. 8) supports the conclusion that the northern San Pedro locality (121) represents a deposit whose age is probably 125 ka, whereas the central San Pedro locality (110) represents a deposit whose age is probably ~80 ka. These data are consistent with the difference in age for the deposits of the "first" terrace based on the aIle/Ile data. Such an interpretation is also consistent with the U-series data that indicate a minimum age of ~110 ka for the deposits found at locality 112 in northern San Pedro (Fig. 3). What is problematic about these observations is that our data indicate that the age of deposits found at 3rd and Mesa Streets (locality 110) is ~80 ka, whereas the age of deposits found at 2nd and Mesa Streets (locality 12606) is ~125 ka. Is there a contact between these two deposits of different ages somewhere along the one-city-block distance separating these two localities? Nearly complete urbanization of this area has not allowed us to identify such a contact in the field, and examination of older maps has not revealed any possibilities either. Another possible interpretation is that the contact is farther north than 2nd and Mesa Streets, but some of the shells from the 2nd and Mesa Street locality have been reworked from older, 125-ka deposits. Ponti (1989) came to similar conclusions about the presence of two ages of deposits in San Pedro and thought that the contact between the two units was somewhere between locality 12606 and locality 112 (Fig. 3).

It is interesting to note that Arnold (1903), Woodring (1935, 1957), Woodring and others (1946), Valentine (1961), and Valentine and Meade (1961) all point out that deposits of the first terrace in northern San Pedro have a distinct warm-water fauna, whereas deposits of the first terrace in central and southern San Pedro have a distinct cool-water fauna. These workers propose various mechanisms to explain this geographic zonation, including transportation of the cool-water species from greater depths by storm waves, reworking from older units, and changes in depth or temperature tolerances. Our data indicate that this geographic zonation exists because there are two ages of deposits represented by the "first" terrace: a ~125 ka unit with a warm-water fauna in northern San Pedro and a ~80 ka unit with a cool-water fauna in southern San Pedro.

OXYGEN ISOTOPE STRATIGRAPHY OF LOW-ELEVATION TERRACES

We can check the validity of some aminostratigraphic correlations by the use of oxygen isotope compositions of fossil mollusks. The oxygen isotope composition of a fossil

TABLE 3.—D/L RATIOS IN VARIOUS AMINO ACIDS OF FOSSIL MOLLUSKS FROM SAN PEDRO AND THE PALOS VERDES HILLS, DETERMINED BY GAS CHROMATOGRAPHY.

Loc.[1]	Unit[2]	Species[3]	Sample #[4]	Leucine	Glutamic Acid	Valine	Alanine	Proline	Phenylalanine
WBK 110	1	*S.*	JW76-60	0.54	0.43	0.39	0.75	0.66	0.51
		P.	JW76-63	0.42	0.37	0.24	0.59	0.43	0.51
		M.	JW77-120	0.51	0.42	0.40	0.75	0.67	0.60
		T.	JW76-61	0.47	0.36	0.30	0.71	0.57	0.52
WBK 121	1	*P.s.*	75-54	0.48	0.39	0.32	0.75	0.54	0.56
		M.n.	76-1	0.67	0.55	0.44	0.83	0.73	0.80
		T.s.	76-2	0.49	0.41	0.35	0.77	0.61	0.58
		Ch.u.	75-55	0.49	0.40	0.34	0.83	0.57	0.57
		Ch.u.	75-56	0.51	0.43	0.38	0.85	0.61	0.57
		S.n.	75-52	0.53	0.42	0.37	0.83	0.66	0.58
		S.n.	75-53	0.54	0.42	0.34	0.87	0.67	0.58
LACM 1210	1	*S.n.*	76-16	0.53	0.42	0.34	0.84	0.64	0.54
LACM 2687	2	*Ch.*	JW77-118-1	0.39	0.38	0.35	0.67	0.43	0.46
		Ch.	JW77-118-2	0.40	0.36	0.40	0.68	0.46	0.48
LACM 332	SPS	*S.n.*	76-6	0.60	0.49	0.41	0.93	0.70	0.69
		S.n.	76-7	0.63	0.50	0.48	0.94	0.74	0.67
		P.s.	76-23	0.64	0.59	0.56	0.93	0.71	0.74
		P.s.	76-23a	0.61	0.55	0.51	0.94	0.67	nd
		M.n.	76-59a	0.79	0.71	0.77	0.94	0.85	0.95
WBK 32	TPS	*S.n.*	76-8	0.69	0.54	0.52	0.94	0.80	0.70
		S.n.	76-9	0.75	0.58	0.57	0.93	0.90	0.73
WBK 53a	LM	*S.*	JW79-81	0.82	0.75	0.62	0.95	0.89	0.81
		S.	JW79-82-1	0.80	0.76	0.61	1.02	0.86	nd
SDS 0288	LM	*S.*	JW79-82-2	0.81	0.71	0.71	0.88	nd	0.70
USGS M6720	4	*E.c.*	76-73	0.66	0.59	0.46	0.87	0.67	0.73
WBK 84	4	*T.g.*	75-76	0.67	0.57	0.42	0.87	0.91	0.89
LDGO 874A	5	*T.g.*	75-62	0.84	0.68	0.63	0.93	0.95	1.00
near LACM 1304	12	*T.g.*	75-61	0.94	0.81	0.85	1.02	0.98	1.02

[1]Locality abbreviations: WBK, Woodring and others (1946); LACM, Los Angeles County Museum of Natural History; SDS, San Diego Society of Natural History; USGS, U.S. Geological Survey; LDGO, Lamont-Doherty Geological Observatory. Samples designated with localities from Woodring and others (1946) were collected in recent years by J. F. Wehmiller and/or co-investigators at or near localities of Woodring and others (1946).

[2]Abbreviations for geologic units: 1, 2, 4, 5, and 12 refer to terraces with those designations made by Woodring and others (1946); SPS, San Pedro sand; TPS, Timms Point silt; LM, Lomita marl.

[3]Abbreviations for genus or species: *S.n.*, *Saxidomus nuttalli*; *S.*, *Saxidomus*; *P.s.*, *Protothaca staminea*; *P.*, *Protothaca*; *M.n.*, *Macoma nasuta*; *M.*, *Macoma*; *T.s.*, *Tivela stultorum*; *T.*, *Tivela*; *Ch.u.*, *Chione undatella*; *Ch.*, *Chione*; *T.g.*, *Tegula gallina*; *E.c.*, *Epilucina californica*.

[4]Amino-acid laboratory number of John F. Wehmiller, University of Delaware.

mollusk or coral is a function of the isotopic composition and temperature of seawater at the time of shell precipitation. Studies from dated terraces on Barbados, New Guinea, and in California have shown that the oxygen-isotopic compositions of mollusks and corals from 80-ka and 125-ka terraces are significantly different from one another and can be used for terrace correlation (Fairbanks and Matthews, 1978; Aharon, 1983; Muhs and Kyser, 1987). We sampled modern and fossil mollusks from terrace deposits in San Pedro and the Palos Verdes Hills in order to verify our aminostratigraphic correlations and to assess paleowater temperatures at the times of terrace formation. Sampling and laboratory methods followed those of Muhs and Kyser (1987).

In their study of the oxygen-isotopic composition of fossil mollusks from 80-ka and 125-ka terraces in California, Muhs and Kyser (1987) observed that both ages of mollusks are enriched in the heavier isotope compared to that of modern shells, but 80-ka shells have the highest $\delta^{18}O$ values. Mean $\delta^{18}O$ values for fossil *Epilucina* from 125-ka terraces on San Nicolas Island, San Clemente Island, and Point Loma (the Nestor terrace) are 0.43 to 0.48 per mil heavier than those of their modern counterparts, suggesting that on *open, exposed coasts*, water temperatures at 125 ka were cooler than at present. Mean $\delta^{18}O$ values for *Epilucina* fossils from 80-ka terraces on San Nicolas and San Clemente Islands are 0.8 to 1.0 per mil heavier than values in modern shells from those localities.

Epilucina shells were taken from three localities on the "second" terrace on the Palos Verdes Hills (localities 12575, 103, and 104) and modern shells from near these localities. Two of these localities (12575 and 103) have aIle/Ile ratios in *Tegula* that suggest correlation with the ~125-ka highstand, whereas the third locality (104) has aIle/Ile ratios that suggest correlation with the ~80-ka highstand. When the $\delta^{18}O$ values for the fossil shells from localities 12475 and 103, along with values from their modern counterparts, are plotted with the San Nicolas Island, San Clemente Island, and Point Loma data, a correlation with the ~125-ka highstand is implied (Table 4 and Fig. 9, in agreement with the amino-acid data. Data from shells at locality 104, when plotted with those of their modern equivalents, are intermediate between the 80-ka and 125-ka trends (Fig. 9). It is possible that the terrace at locality 104 correlates with the ~105-ka highstand recorded as emergent coral reefs on Barbados and New Guinea (Mesolella and others, 1969; Bloom and others, 1974), but because we have no firmly dated 105-ka terraces elsewhere in California, we cannot test this hypothesis in any rigorous fashion.

In the Point Fermin–Cabrillo Beach area, *Epilucina* shells from the "fourth" terrace (locality 83) that we correlated with the 125-ka highstand and from the first terrace near

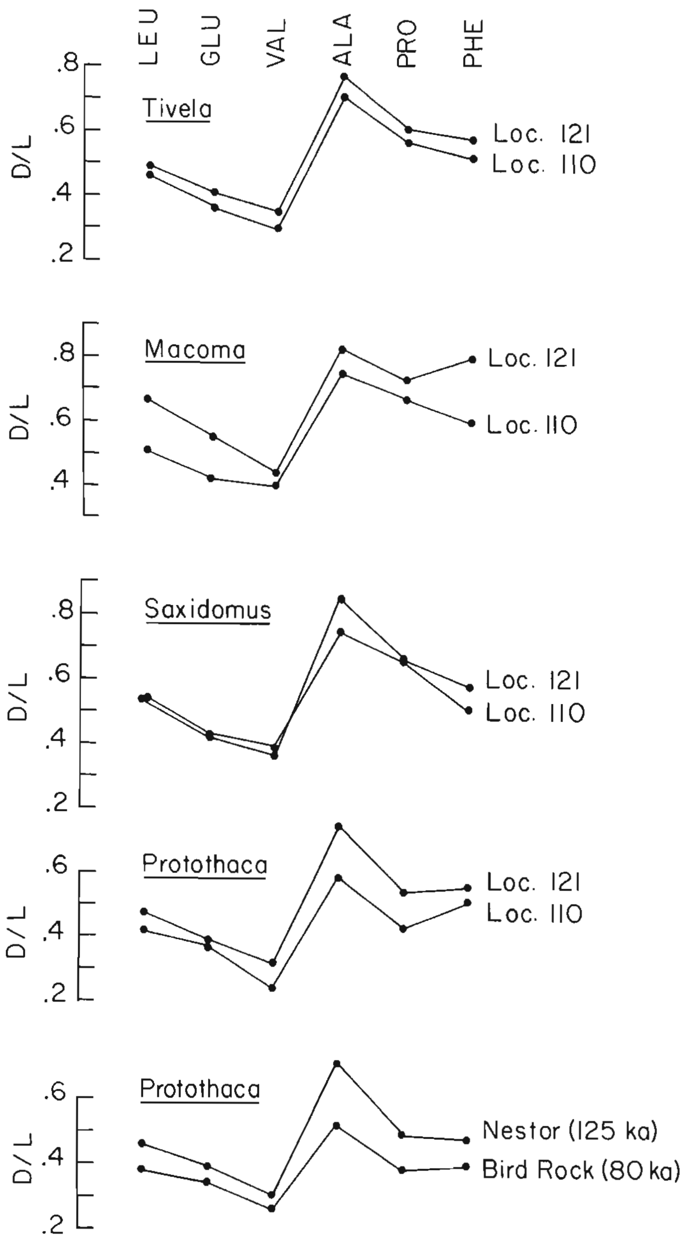

FIG. 8.—D/L ratios in four genera of mollusks for two fossil localities of the first terrace compared to similar ratios for 80-ka and 125-ka terrace fossils from Point Loma near San Diego. Amino-acids: LEU, leucine; GLU, glutamic acid; VAL, valine; ALA, alanine; PRO, proline; PHE, phenylalanine.

Cabrillo Beach (locality 107) that we correlated with the 80-ka highstand were analyzed. Shells from locality 107 (~80 ka) have significantly (0.58 per mil) heavier $\delta^{18}O$ values than shells from locality 83 (~125 ka), which is what we would hypothesize based on their age assignments and their faunal thermal aspects (Table 4 and Fig. 9). Our data for modern shells collected from Cabrillo Beach (south of the breakwater) have values that are not significantly different from those from locality 107 (Table 4), and we suspect that these are fossils that have been reworked onto the

TABLE 4.—STABLE-ISOTOPE COMPOSITION OF MODERN AND FOSSIL MOLLUSKS FROM MARINE TERRACES IN THE PALOS VERDES HILLS (PVH) AND SAN PEDRO, CALIFORNIA.

Location	Terrace	Genus	Fossil Loc.	$\delta^{13}C$(PDB) (‰)	$\delta^{18}O$(PDB) (‰)	$\delta^{18}O$ Mean±s.d. (‰)
PVH	Modern	*Epilucina*	near 12575	2.76	0.48	
				3.65	0.44	
				2.07	0.35	0.42±0.05
PVH	Modern	*Epilucina*	near 103	2.22	0.28	
				1.95	0.36	
				2.57	0.52	0.39±0.10
PVH	Modern	*Epilucina*	near 104	2.53	0.33	
				2.70	0.32	
				2.49	0.22	0.29±0.05
PVH	2	*Epilucina*	12575	1.80	0.84	
				2.40	0.97	
				1.87	1.01	0.94±0.07
PVH	2	*Epilucina*	103	2.28	0.61	
				2.27	0.96	
				2.54	0.94	0.84±0.16
PVH	2	*Epilucina*	104	2.86	0.73	
				2.76	1.13	0.93±0.20
San Pedro	Modern	*Epilucina*	near 107	3.12	0.92	
				2.45	0.87	
				1.52	1.06	0.95±0.08
San Pedro	1	*Epilucina*	107	2.07	1.27	
				1.24	0.97	
				1.18	1.02	1.08±0.13
San Pedro	4	*Epilucina*	83	2.28	0.42	
				2.29	0.51	
				0.87	0.56	0.50±0.06
San Pedro	Modern	*Protothaca*	near 108	0.85	−0.37	
				1.15	−0.25	
				0.82	−0.16	−0.26±0.09
San Pedro	1	*Protothaca*	108	0.88	0.15	
				−0.28	0.23	
				−0.32	0.45	0.28±0.13
San Pedro	1	*Protothaca*	12576	0.91	−0.07	
				−0.05	−0.70	
				0.55	−0.27	−0.35±0.26

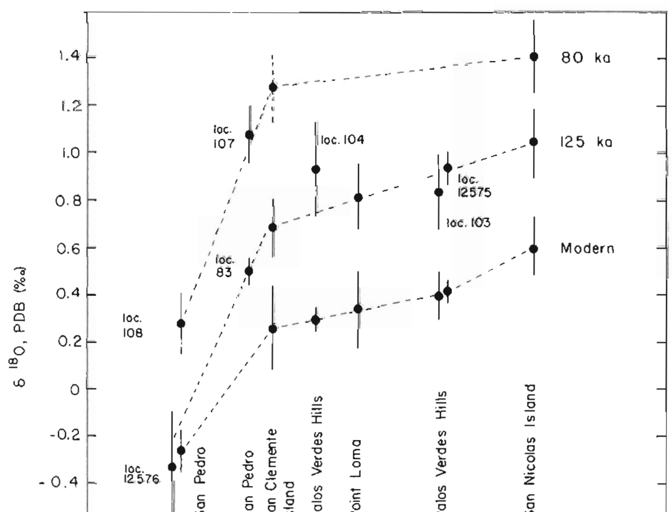

FIG. 9.—Oxygen isotope composition of terrace fossils shown as a function of age for dated terraces on San Clemente Island, Point Loma, and San Nicolas Island and their correlation with fossil localities in the Palos Verdes Hills and San Pedro. All fossils are *Epilucina* with the exception of localities those at 12576 and 108, which are *Protothaca*. Oxygen isotope data for dated terraces are from Muhs and Kyser (1987).

modern beach. The $\delta^{18}O$ composition of the modern shells indicates water temperatures ~1.5°C cooler than at San Nicolas Island, which has a current mean water temperature of ~15°C (Lynn, 1967). Measured water temperatures in the Palos Verdes Hills–San Pedro area are about 16°C (Lynn, 1967).

Within San Pedro, *Epilucina* is not found at most fossil localities, owing to the lack of rocky-shore environments in this area at the time of terrace formation. We therefore analyzed specimens of *Protothaca* that are common in the terrace deposits. Because of possible species effects on oxygen isotope composition, we consider these data independently and compare them to modern *Protothaca* isotopic compositions rather than to the *Epilucina* data. Shells from locality 12576 in northern San Pedro and Crawfish George's in southern San Pedro are estimated to be ~125 ka and ~80 ka, respectively, based on aminostratigraphic correlations. Analyses of modern *Protothaca* shells from Cabrillo Beach, north of the breakwater, indicate that shells from locality 12576 (~125 ka) are not significantly different from the modern shells (Table 4 and Fig. 9), but shells from Crawfish George's (~80 ka) have, as expected, significantly heavier values than either the modern or ~125-ka shells. These data support the aminostratigraphic correlations and are consistent with the generally warm-water aspect of terrace faunas in northern San Pedro and the cool-water aspect of terrace faunas from Crawfish George's (Valentine, 1961; Valentine and Meade, 1961).

Approximate paleotemperature reductions at 125 ka (on the exposed part of the Palos Verdes Hills) and at 80 ka (in San Pedro) can be calculated. In making these calculations, we have assumed that (1) sea level was at −5 m relative to present at 80 ka and at +6 m relative to present at 125 ka and (2) a $\delta^{18}O$ (PDB) shift of 0.11 per mil is equivalent to 10 m of sea level (Fairbanks and Matthews, 1978) and that 0.23 per mil is equivalent to about 1°C. Based on the data from localities 103 and 12575 and modern samples collected near those localities, we infer temperature reductions of 2.3 to 2.6°C at 125 ka on the open, exposed parts of the Palos Verdes Hills. These reductions agree with estimates made for other southern California localities by Muhs and Kyser (1987). As discussed earlier, in the protected parts of San Pedro, water temperatures at 125 ka appear to have been as warm as or warmer than those of the present. However, based on the data from shells collected at Crawfish George's, water temperatures around San Pedro at 80 ka appear to have been about 2.1°C cooler than at present. This temperature reduction is consistent with the cool-water aspect of the terrace fauna (Valentine and Meade, 1961).

One problem that our data and those of Muhs and Kyser (1987) present is the implication of cooler than present paleowater temperatures for some localities at ~125 ka. These observations appear to conflict with observations made earlier of extralimital southern species (i.e., warm-water faunas) present in many terrace deposits that have been correlated with the ~125-ka highstand (cf. Kennedy and others, 1982). It should be noted, however, that the four localities where isotopic data show cooler than present waters at 125 ka (San Nicolas Island, San Clemente Island, Point Loma, and part of the Palos Verdes Hills) are all open, exposed environments that experience strong onshore winds and have the potential for particularly strong upwelling. In contrast, a locality such as 12576 in northern San Pedro (Fig. 3) was in a protected embayment at the time of deposition and would not have been a likely environment for significant upwelling. The oxygen-isotopic composition of shells from the latter environment do not indicate water temperatures that were significantly different from modern water temperatures. Therefore, during the highstand at 125 ka, open coastal areas may have been exposed to stronger onshore winds and thus may have been subject to greater upwelling, which would result in cooler water temperatures on average and could explain the heavier oxygen-isotopic composition in fossils from those localities. Protected embayments, such as those adjacent to northern San Pedro, would not have been subject to significant upwelling, which would explain the similarity to present oxygen isotope temperatures in fossils from such localities. Such a model is consistent with the faunal data as well: deposits from the 125-ka terraces on the open, exposed coasts of San Nicolas Island and Point Loma contain a number of extralimital northern species as well as extralimital southern species (Valentine and Meade, 1961; Vedder and Norris, 1963). In contrast, fossil localities that occur in protected embayments are dominated by extralimital southern species. Kennedy (1988) suggested that during the highstand at 125 ka, greater seasonality may have prevailed on the California coast, possibly as the result of orbital forcing.

Increased frequency or intensity of upwelling as a possible cause for the cooler water temperatures at 125 ka on the open, exposed parts of the California coast may be explained by a recent model presented by Bakun (1990). He suggested that during periods of global warming (such as that envisioned for the 21st century due to greenhouse-gas buildup), continental-margin areas would become warm faster than nearshore ocean waters. This would increase the offshore-onshore pressure gradient, which in turn would increase the strength of alongshore winds. The increased wind strength would enhance the potential for wind-driven upwelling and result in cooler water temperatures along certain coastlines even though the climate on the adjacent continent would be relatively warm. Such a model invites testing for the last interglacial highstand in California at 125 ka and is in part supported by the data presented here.

AMINOSTRATIGRAPHY OF HIGHER MARINE TERRACES AND NON-TERRACED MARINE DEPOSITS

We cannot generate age estimates or attempt lateral correlation for higher marine terraces in the Palos Verdes Hills because of limited data. However, ratios of aIle/Ile for *Tegula* collected from higher terraces given by Muhs (1984) and D/L ratios in this genus collected from the fourth, fifth and twelfth terraces given here (Table 3) indicate that *Tegula* continues to show increasing values over longer time periods. This suggests that should more fossil localities be found, lateral correlation of higher terraces using aminostratigraphy might be possible.

Mean leucine D/L values in *Saxidomus* shells collected from the Palos Verdes sand (from locality 121), the San Pedro sand, the Timms Point silt, and the Lomita marl are

0.53, 0.62, 0.72, and 0.81, respectively (Table 3 and Wehmiller, 1990). These ratios are consistent with the stratigraphic relations among the units as given by Woodring and others (1946). The Palos Verdes sand at locality 121 in northern San Pedro is probably ~125 ka, as discussed previously. The three older marine units appear to be mid-Pleistocene, in agreement with the conclusions of Ponti (1989), who studied these units in considerable detail. If the Lomita marl was deposited during the Pliocene, as suggested by the data of Obradovich (1968), we would expect D/L ratios in *Saxidomus* to be around 0.90 or greater. Wehmiller and others (1977) reported leucine D/L ratios of 0.90 to 0.93 for *Saxidomus* shells from the Fernando and San Diego Formations, which are Pliocene.

IMPLICATIONS FOR LATE QUATERNARY TECTONICS

Marine-terrace data are particularly suitable for studies of Quaternary tectonics because terrace platforms begin as essentially horizontal surfaces (in a shore-parallel sense) that form near sea level. After formation, these platforms can be uplifted, submerged, warped, or faulted depending on the tectonic setting. Along the Pacific Coast of North America, numerous studies have documented tectonic deformation of marine terraces (Birkeland, 1972; Ku and Kern, 1974; Bradley and Griggs, 1976; Kern, 1977; Lajoie and others, 1979, 1982; Muhs and Szabo, 1982; Merritts and Bull, 1989; Rockwell and others, 1989; Hanson and others, 1990; Kelsey, 1990; Lettis and others, 1990; McInelly and Kelsey, 1990; Muhs and others, 1990).

To calculate an uplift rate for a marine terrace, it is necessary to know the age of the terrace, its present elevation (represented by the elevation of the shoreline angle, the closest approximation to mean sea level at the time of terrace formation), and the paleosea level at the time of terrace formation. A number of terrace segments have been correlated here with the well-known 80-ka and 125-ka highstands, based on amino-acid ratios and oxygen isotope composition of the terrace mollusks. The shoreline-angle elevations have been estimated using topographic profiles. Paleosea-level elevations at 80 ka and 125 ka can be estimated using studies from other areas. On tectonically stable coasts distant from plate boundaries, the 125-ka terrace is commonly the only terrace present and is usually 2 to 10 m above present sea level (Ku and others, 1974; Neumann and Moore, 1975; Harmon and others, 1983). Following the lead of other workers (e.g., Bloom and others, 1974), we assume that sea level at 125 ka was about +6 m relative to present. For the 80-ka highstand, paleosea level is usually estimated by calculating an uplift rate for the 125-ka terrace and assuming that this rate is applicable for the 80-ka terrace. The elevation of the 80-ka terrace can then be used to calculate a paleosea level. Unfortunately, estimates of paleosea level derived in this manner differ from coast to coast. The latest estimates for the Huon Peninsula of New Guinea suggest that sea level at 80 ka was −19 m relative to present (Chappell and Shackleton, 1986), whereas estimates from Baja California and southern California suggest that −5 m is more appropriate (Rockwell and others, 1989; Kennedy and others, 1990; Muhs and others, 1988, 1992). For this study, we assume a paleosea level of −5 m relative to present, as that value seems to be most consistent for other localities studied on the Pacific Coast of North America.

A cross section in the area around Point Fermin (Fig. 3) shows how terraces have been displaced by the Cabrillo fault (Fig. 10). The "second" terrace on the upthrown side of the Cabrillo fault has amino-acid ratios that correlate with the "first" terrace on the downthrown side of the fault, but the shoreline-angle elevations of these two terraces are different (~46 m on the upthrown side vs. ~30 m on the downthrown side). Both terraces are correlated with the 80-ka highstand as discussed earlier. Using the assumed −5-m paleosea-level, uplift rates of 0.64 m/ka are derived for the upthrown side of the fault and 0.44 m/ka for the downthrown side of the fault. The difference in uplift rates, 0.20 m/ka, is an approximation of the average rate of vertical movement of the Cabrillo fault over the last 80 ka. This estimate is lower by a factor of two to three relative to Holocene vertical rates of 0.4 to 0.7 m/ka estimated for offshore portions of the Cabrillo fault by Fischer and others (1987). It is possible that the rate of vertical movement varies spatially along this fault or has increased through time.

Our age assignments and estimates of shoreline-angle elevations result in a range of uplift rates for different parts of the Palos Verdes peninsula (Fig. 11). Over most of the westernmost part of the peninsula, from Lunada Bay to just southeast of Portuguese Bend (Fig. 2), the 46-m "second" terrace, with its age assignment of ~125 ka, results in an uplift rate of about 0.32 m/ka. This rate compares favorably with rates derived for other parts of the California and northern Baja California coast that are dominated by what are thought to be strike-slip faults (Ku and Kern, 1974; Kern, 1977; Muhs and Szabo, 1982; Muhs, 1983, 1985; Rockwell and others, 1989; Hanson and others, 1990; Lettis and others, 1990; Muhs and others, 1990). On the upthrown side of the Cabrillo fault, as discussed earlier, the uplift rate is significantly higher, on the order of 0.56 m/ka (if calculated from the ~125-ka "fourth" terrace) to 0.64 m/ka (if calculated from the ~80-ka "second" terrace). On the downthrown side of the Cabrillo fault, the uplift rate based

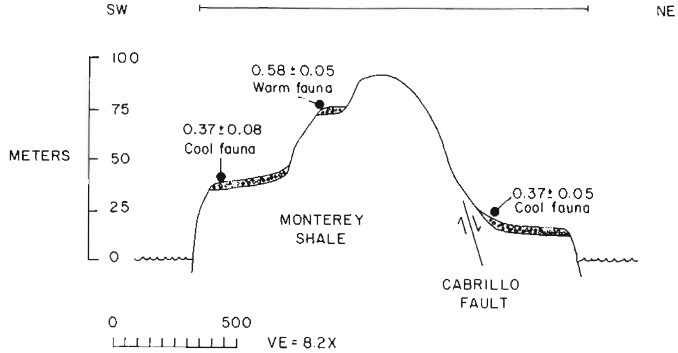

FIG. 10.—Geologic cross section across Point Fermin (location shown in Fig. 3) showing terraces, the Cabrillo fault, thermal aspects of terrace faunas, and aIle/Ile ratios in *Tegula*.

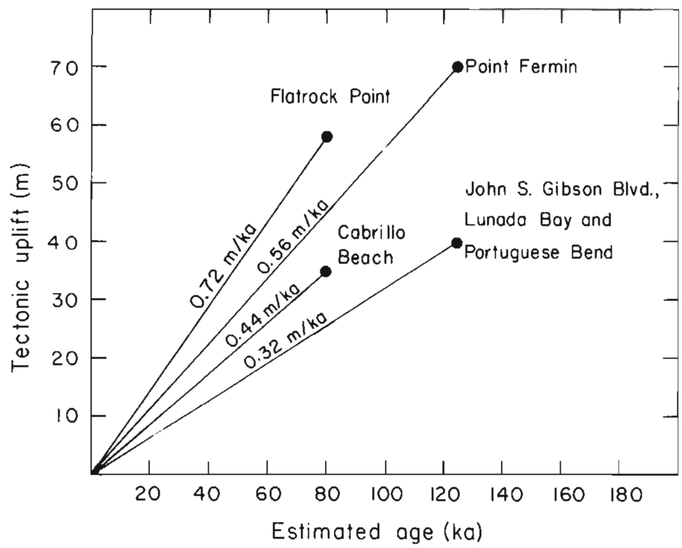

FIG. 11.—Amount of tectonic uplift of marine terraces at various localities around the Palos Verdes peninsula and San Pedro shown as a function of estimated terrace age. Slopes of lines are uplift rates. Rate given for Flatrock Point is a maximum value, based on an 80-ka-age estimate; rate given for the terrace at John S. Gibson Boulevard is a maximum value based on an estimated maximum shoreline-angle elevation of 46 m.

on the 80-ka terrace is lower, on the order of 0.44 m/ka. However, this rate is still higher than those for most other parts of the peninsula. It is difficult to calculate uplift rates based on the 125-ka terrace east of the Cabrillo fault because shoreline angles in this area are neither exposed in the field nor easily estimated from topographic profiles. At locality 12576, the wave-cut platform has an elevation of ~19 m, yielding a minimum uplift rate of around 0.10 m/ka. Based on interpretation of the terrace map by Woodring and others (1946), the maximum possible elevation for the shoreline angle of this terrace is on the order of 46 m, which yields an uplift rate of 0.32 m/ka, similar to the rates for the other parts of the peninsula.

The locality for which we have the greatest uncertainty in uplift rate is the "second" terrace at Flatrock Point, locality 104 (Fig. 2). The terrace platform here is close to the shoreline angle and has an elevation of about 53 m. Alle/Ile ratios in *Tegula* correlate the terrace with the 80-ka highstand (Fig. 7). If this correlation is correct, these data result in an uplift rate of 0.72 m/ka, which is greater than the uplift rates for most of the Palos Verdes Hills and northern San Pedro by more than a factor of two (Fig. 11). On the other hand, stable-isotope data in *Epilucina* indicate that this terrace could correlate with the ~125-ka or ~105-ka highstands which would yield uplift rates of 0.38 m/ka and 0.52 m/ka, respectively, assuming a paleosea level of −2 m at 105 ka (Rockwell and others, 1989). We cannot reject any of the uplift-rate estimates until we have an unambiguous age estimate for this terrace. As pointed out earlier, Riccio and Mills (1977) cited evidence of a previously unreported fault in this area. However, their data showed that the terrace at locality 104 would be on the downthrown side of this fault, which should not yield higher than average uplift rates. Further field investigations in the Flatrock Point area are warranted, both for terrace-age estimates and to evaluate the structural relations in this area.

The estimated late Quaternary uplift rates for the Palos Verdes Hills–San Pedro area, ranging from 0.32 to 0.64 m/ka (and possibly as high as 0.72 m/ka), represent approximate values for the rate of vertical movement of the Palos Verdes Hills fault. If marine deposits whose age and elevations were known existed on the northeast side of the fault, we could calculate a more precise rate of vertical movement, but it is not clear from the terrace map of Woodring and others (1946) where such deposits might be or how they might be correlated. Our uplift rates are in broad agreement with Holocene vertical rates of 0.1 to 0.4 m/ka estimated for offshore portions of the Palos Verdes Hills fault by Fischer and others (1987).

CONCLUSIONS

Studies of the terraces in the Palos Verdes Hills and San Pedro areas (and calibration areas such as San Nicolas Island) yield the following conclusions:

1. Amino-acid ratios in shells from dated terraces on San Nicolas Island show that the gastropod *Tegula* is an excellent discriminator for 80-ka and 125-ka deposits; in contrast, the bivalve *Epilucina* cannot distinguish these two ages of deposits.
2. Amino-acid data from *Tegula* and *Protothaca* and oxygen isotope data from *Epilucina* indicate that most segments of the lowest terrace in the Palos Verdes peninsula (mapped as the "second" terrace by Woodring and others, 1946) are correlative with the 125-ka highstand. However, at Point Fermin (and possibly at Flatrock Point), segments of the "second" terrace are correlative with the ~80-ka highstand.
3. Amino-acid data from *Tegula, Protothaca, Macoma*, and *Tivela* and oxygen isotope data for *Protothaca* indicate that deposits of the "first" terrace in San Pedro actually consist of sediments with two ages: an older (~125 ka) deposit that occurs in northern San Pedro and is characterized by a warm-water fauna, and a younger (~80 ka) deposit that occurs in southern San Pedro and is characterized by a cool-water fauna.
4. Oxygen isotope data from *Epilucina* and *Protothaca* indicate that on open, exposed parts of the Palos Verdes peninsula, ocean temperatures during the 125-ka highstand were cooler than those of the present, similar to what has been observed on other parts of the California coast that have open, exposed environments. Paleotemperature calculations indicate that water temperatures at 125 ka were 2.3 to 2.6°C cooler than the present, possibly as the result of more frequent or more intense upwelling when continental temperatures were actually warmer than present. In contrast, in the protected-embayment type of environment that has characterized the San Pedro area, ocean temperatures during the 125-ka highstand were probably at least as warm as present temperatures. However, even in the relatively protected environment of the San Pedro area, ocean temperatures

during the 80-ka highstand were significantly cooler (~2.1°C) than at present.

5. Correlation of the lowest terraces around Point Fermin indicates that the Cabrillo fault has experienced about 16 m of vertical movement in the last 80 ka, for a vertical-slip rate of 0.20 m/ka. Late Quaternary vertical-movement rates for the Cabrillo fault determined in this study are significantly lower than Holocene rates of vertical movement estimated by other workers for offshore portions of this fault.
6. Uplift rates around the rest of the peninsula vary from 0.32 m/ka to possibly as high as 0.72 m/ka. For most parts of the Palos Verdes peninsula, late Quaternary uplift rates estimated in this study are comparable to Holocene rates of vertical movement estimated by other workers for offshore portions of the Palos Verdes Hills fault.

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